Search for Heavy Top-like Quark Pair Production in the Dilepton Final State in pp Collisions at $\sqrt{s} = 7$ TeV

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The CMS Collaboration

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Available on CMS information server — CMS AN -2011/509

The Compact Muon Solenoid Experiment
Analysis Note
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The results of a search for pair production of a heavy top-like quark, t', in the decay mode $t'\bar{t}' \to bW^+\bar{b}W^- \to b\ell^+\nu\,\bar{b}\ell^-\bar{\nu}$ are presented. The search is performed in a data sample corresponding to a total integrated luminosity of 4.7 fb^{-1} of pp collisions at a centre-of-mass energy of 7 TeV, collected by the CMS experiment at the LHC. The observed number of events agrees with the standard model prediction, and no evidence of $t'\bar{t}'$ production is found. Upper limits on the production cross section as a function of t' mass are presented. A t' with a mass below 552 GeV/c^2 is excluded at the 95% C.L.

http://cms.cern.ch/iCMS/analysisadmin/cadi?ancode=EXO-11-050

- Thanks to the ARC:
  Philip Harris (MIT), Ia Iashvili (Buffalo), Isabel Josa Mutuberria (Madrid, CIEMAT), Mayda Velasco (Northwestern) (Chairperson)

Motivation

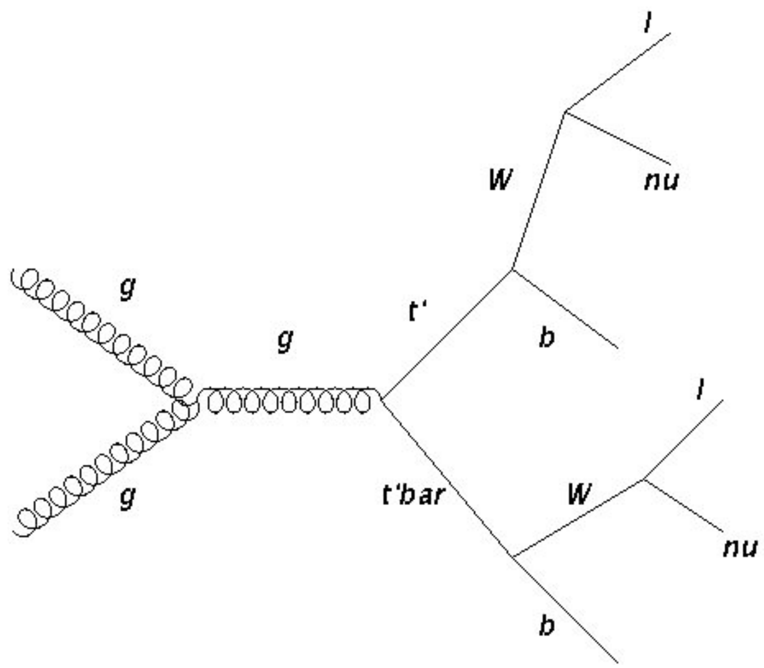
- 4^{th} generation of fermions is a simple extension to the SM
- With a 4^{th} generation, indirect bounds on M_H can be relaxed
- May possess sufficient intrinsic matter-antimatter asymmetry to be relevant to the baryon asymmetry of the Universe

- Lepton-Photon result (1.14/fb): $m_{t'} > 422$ GeV
  - http://cdsweb.cern.ch/record/1376672/files/EXO-11-050-pas.pdf

- Tevatron limits already exceeded:
  - CDF: $m_{t'} > 358$ GeV (http://arxiv.org/abs/1107.3875)
  - D0: $m_{t'} > 285$ GeV (http://arxiv.org/abs/1104.4522)

- We search in the dilepton final state, where

$$t'\bar{t}' \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}, \text{ where } \ell = e \text{ or } \ell = \mu.$$



opposite sign dileptons
2 b jets
MET

- Datasets: DoubleElectron, DoubleMu, MuEG
  - High p_T dilepton triggers
  - May10th rereco + Prompt v4 + Aug05th rereco + Prompt v6 + 2011B Data (4.7 fb^{-1})
- Summer 11 MC

Analysis Strategy

- Use opposite sign dilepton SUSY analysis lepton selection (SUS-10-007) plus MET cut and b tagging requirement
  - purpose of this preselection is to reject events other than t’t’bar or ttbar, and it is used as a control region for data-MC comparison
- Define a signal region to separate t’t’bar signal from ttbar background
- Estimate residual backgrounds using data driven methods where possible
- Perform the analysis as counting experiment
- In the absence of an excess, set 95% C.L. upper limits on t’ pair production cross sections and lower limit on t’ mass

Event selection

- Event cleaning: if >= 10 tracks; at least 25% purity; at least 1 good DA vertex (not isFake, ndf > 4, rho < 2 cm, z < 24 cm)
- 2 opposite sign isolated leptons with p_T > 20 GeV and |eta| < 2.5 (2.4) for e (μ)
- ≥2 pf jets with p_T > 30 GeV, |eta| < 2.5
  - loose pfjet ID (L1FastL2L3 corrected)
  - ΔR > 0.4 from all leptons passing analysis selection
  - exactly 2 b tags: TCHEM (changed from ≥2 in 1.14/fb analysis)
- MET > 50 GeV (changed from 30 GeV in 1.14/fb analysis)
- Z veto: $76 < m_{ll} < 106$ GeV veto (for SF leptons)
- $m_{ll} > 12$ GeV to veto low mass resonances (SF leptons)

Preselection Yields (4.7 fb^{-1})

Paper and AN

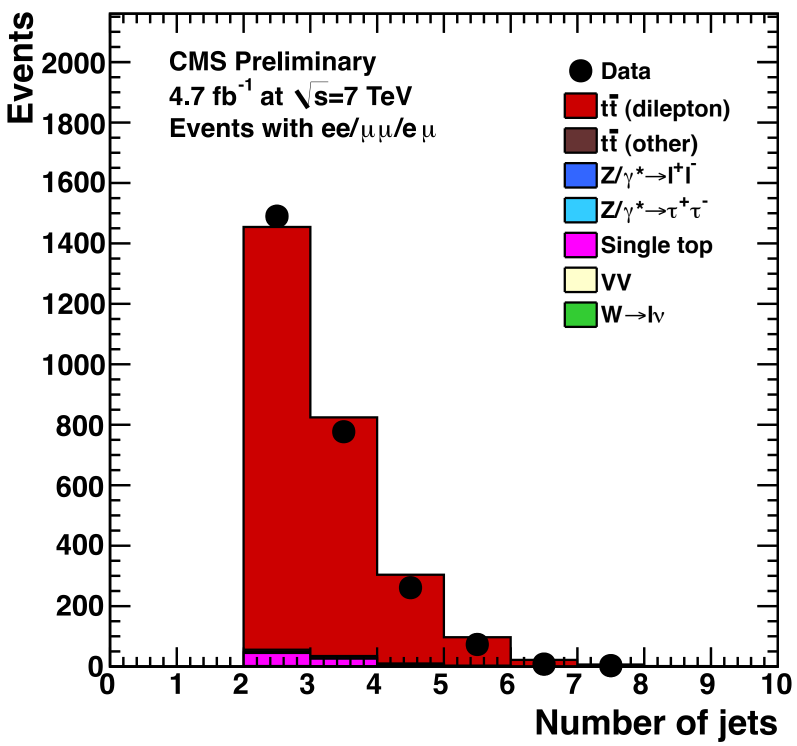
Sample	ee	$\mu\mu$	$e\mu$	all
$t'\bar{t}'$, $M_{t'} = 350\,\mathrm{GeV}/c^2$	22.7 ± 2.0	27.2 ± 2.1	56.1 ± 3.1	106.0 ± 4.2
$t'\bar{t}'$, $M_{t'} = 400\,\mathrm{GeV}/c^2$	10.0 ± 0.9	13.0 ± 1.0	27.7 ± 1.4	50.7 ± 1.9
$t'\bar{t}'$, $M_{t'} = 450\,\mathrm{GeV}/c^2$	5.3 ± 0.4	6.0 ± 0.5	14.3 ± 0.7	25.7 ± 1.0
$t'\bar{t}'$, $M_{t'} = 500\,\mathrm{GeV}/c^2$	2.8 ± 0.2	3.1 ± 0.2	6.3 ± 0.3	12.2 ± 0.5
$t'\bar{t}'$, $M_{t'} = 550\,\mathrm{GeV}/c^2$	1.7 ± 0.1	1.7 ± 0.1	3.4 ± 0.2	6.8 ± 0.3
$t'\bar{t}'$, $M_{t'} = 600\,\mathrm{GeV}/c^2$	0.8 ± 0.1	1.0 ± 0.1	2.1 ± 0.1	3.9 ± 0.2
$t\bar{t} \to \ell^+\ell^-$	494.2 ± 11.2	622.3 ± 12.1	1490.7 ± 19.1	2607.2 ± 25.3
$t\bar{t} \to$ fake	7.3 ± 1.4	0.5 ± 0.3	10.7 ± 1.6	18.4 ± 2.1
W + jets	< 1.8	< 1.8	< 1.8	< 1.8
DY$\to \ell^+\ell^-$	2.7 ± 1.4	1.5 ± 0.9	0.5 ± 0.5	4.8 ± 1.7
Di-boson	0.5 ± 0.1	1.0 ± 0.1	1.8 ± 0.2	3.3 ± 0.3
Single top	14.7 ± 0.9	18.3 ± 1.0	44.1 ± 1.6	77.1 ± 2.1
Total Background	519.4 ± 11.4	643.6 ± 12.2	1547.8 ± 19.3	2710.9 ± 25.5
Data	510	615	1487	2612

Uncertainties are statistical only

- MC events are weighted to match trigger efficiency, b tagging efficiency, and number of vertices distribution in data
- 97% of MC background yield is from ttbar
- Data-MC agreement is reasonable
- Plots on next slide

Data-MC comparison

AN



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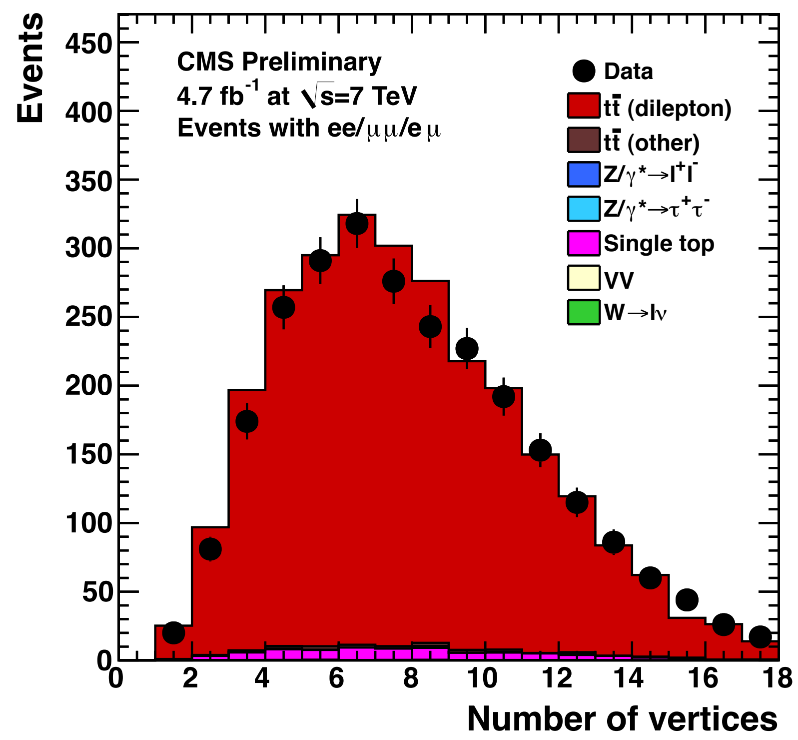
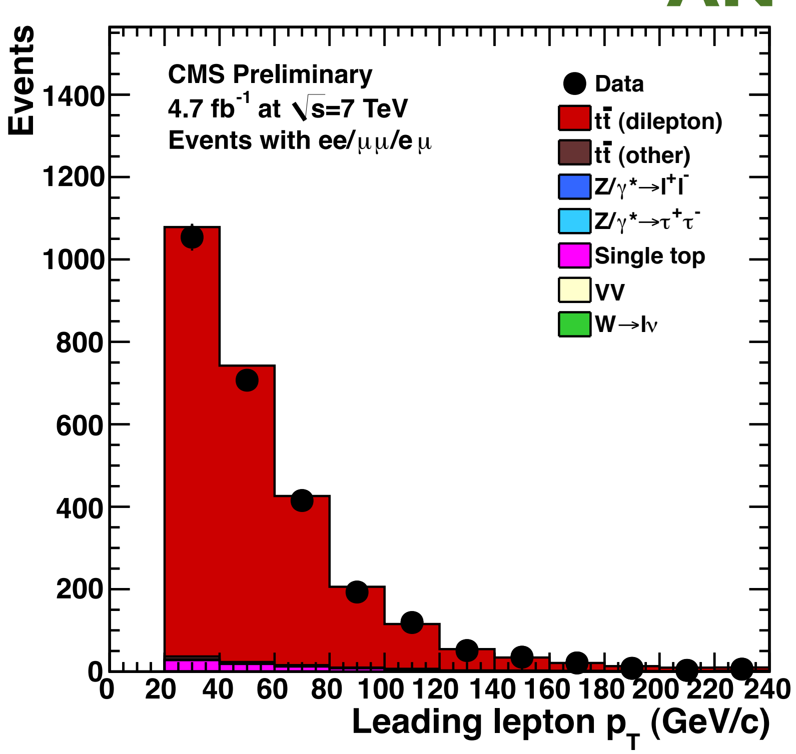


- Vertex reweighting has been applied to MC
- Selected plots: #jets, #vertices, leading lepton and jet p_T, MET
- More plots in backup
- Data and MC agreement is reasonable

AN



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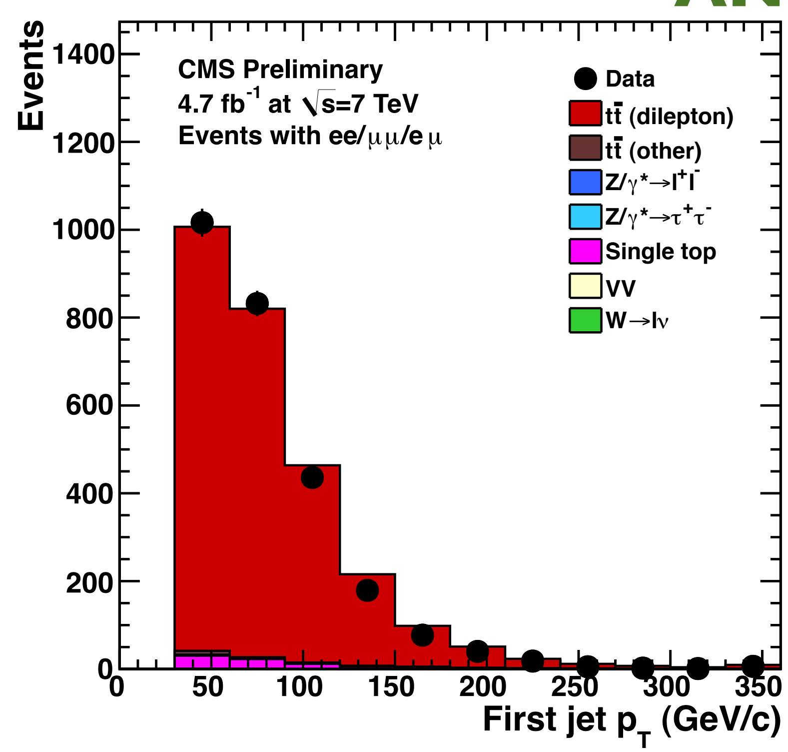

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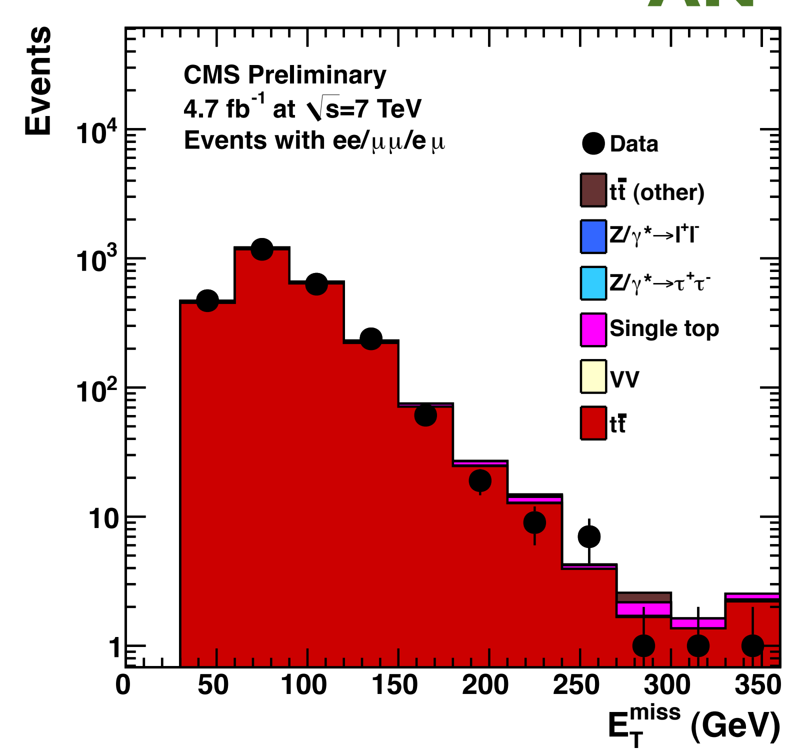
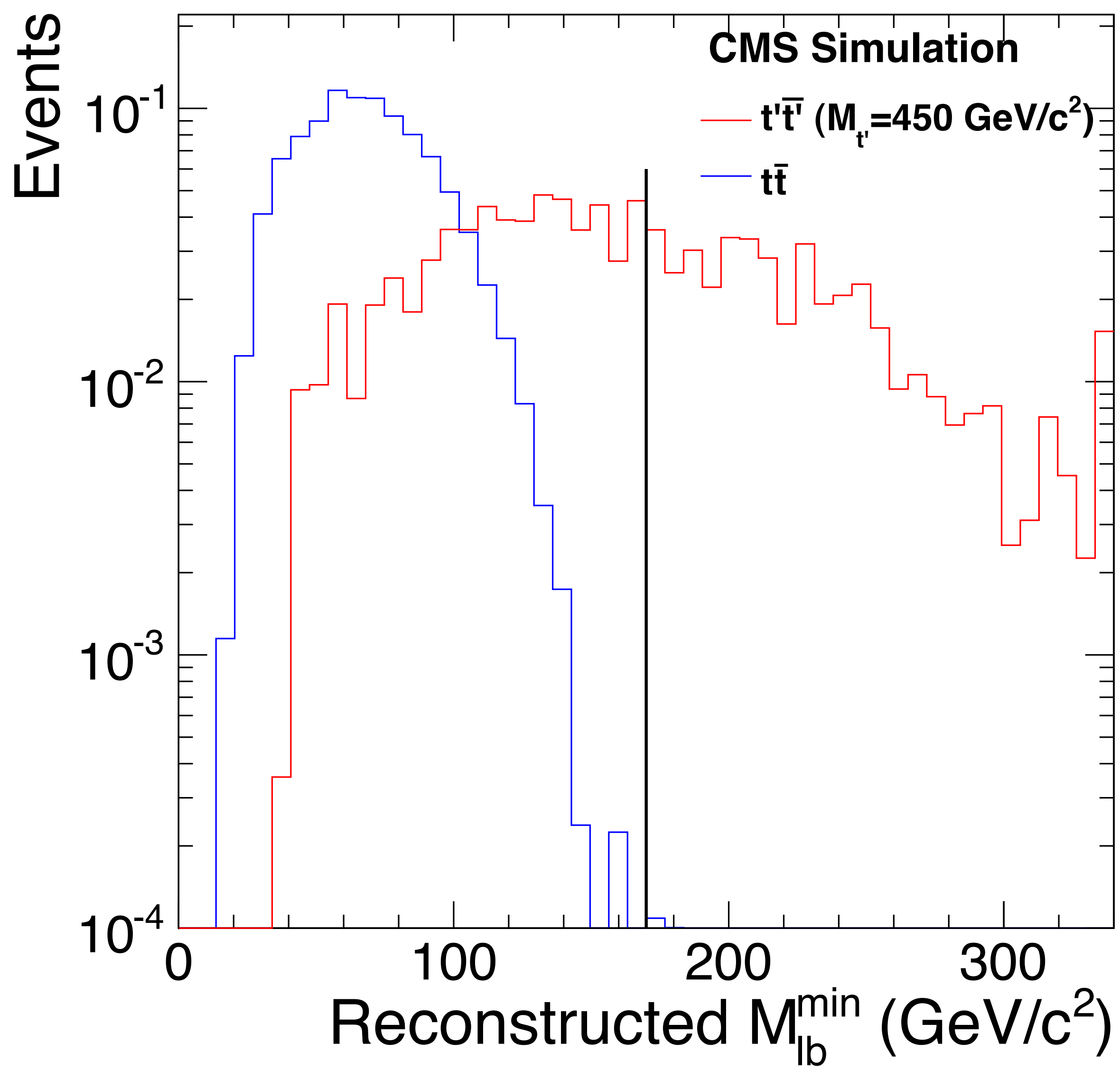


Defining the Signal Region

- We can discriminate t' from t based on mass
- For leptonic decay, invariant mass of the lepton and b is constrained as $M_{lb}^2 < M_{t/t'}^2 - M_W^2$

AN



- We have 2 leptonic decays, so don't know which lepton goes with which b
  - 4 possible combinations
- To remove top background, require all 4 M_{lb} > 170 GeV
  - equivalently, M_{lb}^{min} > 170 GeV
- Reduces ttbar by 10^4, and t't'bar by only ~50% (see plot)
- Very small number of ttbar events still appear in signal region
  - mostly when at least one of the 2 bs is not from top decay
    - mistag(s) or extra real b(s)
  - also some badly mis-measured b jets
- Signal region definition is changed since 1.14/fb analysis (only 2 of the 4 M_{lb} had to be >170 GeV).
  - requires new data-driven background estimation methods

Background prediction

- Divide the background events into 4 categories:
  - Category I: events with mistagged b(s) and real leptons
  - Category II: events with fake lepton(s) and real bs
  - Category III: events with 2 real bs and 2 real leptons
  - Category IV: events with mistagged b(s) and fake lepton(s)
- Data-driven predictions for Categories I and II using b mistag rate and lepton fake rate (also covers Category IV)
- No data driven method for Category III: use MC

Category I: Mistag background estimation

- Mistag background: 1 or both the b jets are mistags
- Estimate from data using method analagous to lepton fake rate, but instead using mistag rate m_i for each jet
  - Single mistag background contribution, $N_{1\text{-mistag}}$, from events in 1 b-tag bin weighted by $m_i/(1-m_i)$
  - Double mistag background contribution, $N_{2\text{-mistags}}$, from events in 0 b-tag bin weighted by $m_i/(1-m_i) \times m_j/(1-m_j)$
  - Final prediction from $N_{1\text{-mistag}}-N_{2\text{-mistags}}$, because $N_{2\text{-mistags}}$ is already counted twice in $N_{1\text{-mistag}}$
- We see under-prediction of up to 50% in MC closure test
  - assign 100% systematic uncertainty (but no scaling to avoid over-prediction)
- Prediction in data: 0.74±0.27±0.74

Category 2: Fake lepton background estimation

- This method is unchanged from the 1.14/fb analysis
- We estimate the contribution from fake leptons using the data-driven tight-to-loose method described in CMS AN-2010/257
  - measure tight-to-loose fake rates as a function of lepton p_T and eta
  - estimate number of fakes in data based on number of fakeable objects (FOs)
  - Expect fake background dominated by ttbar decaying to lepton+jets
- We find zero FOs, thus our fake estimate is 0 events
- Take upper limit from weight of one FO, giving estimate of $0_{-0}^{+0.4}$
- Consistent with MC where we also see 0 events with fake leptons

Category III and total background

- Signal region MC yields: **AN (and paper for 3 t' samples only)**

Sample	ee	$\mu\mu$	eμ	all
$t'\bar{t}'$, $M_{t'} = 350\,\mathrm{GeV}/c^2$	5.10 ± 0.96	7.71 ± 1.10	11.35 ± 1.35	24.16 ± 1.98
$t'\bar{t}'$, $M_{t'} = 400\,\mathrm{GeV}/c^2$	3.28 ± 0.48	5.14 ± 0.60	10.49 ± 0.87	18.91 ± 1.16
$t'\bar{t}'$, $M_{t'} = 450\,\mathrm{GeV}/c^2$	2.24 ± 0.29	2.48 ± 0.29	6.17 ± 0.46	10.88 ± 0.62
$t'\bar{t}'$, $M_{t'} = 500\,\mathrm{GeV}/c^2$	1.36 ± 0.16	1.82 ± 0.18	3.15 ± 0.23	6.32 ± 0.33
$t'\bar{t}'$, $M_{t'} = 550\,\mathrm{GeV}/c^2$	0.95 ± 0.11	0.98 ± 0.10	1.92 ± 0.14	3.86 ± 0.21
$t'\bar{t}'$, $M_{t'} = 600\,\mathrm{GeV}/c^2$	0.53 ± 0.06	0.56 ± 0.06	1.25 ± 0.09	2.34 ± 0.12
$t\bar{t} \to \ell^+\ell^-$	0	0.53 ± 0.34	0	0.53 ± 0.34
$t\bar{t} \to$ fake	0	0	0	0
$W +$ jets	0	0	0	0
DY$\to \ell^+\ell^-$	0.66 ± 0.66	0	0	0.66 ± 0.66
Di-boson	0.05 ± 0.04	0.12 ± 0.05	0.12 ± 0.05	0.29 ± 0.08
Single top	0	0.12 ± 0.09	0.36 ± 0.16	0.48 ± 0.18
Total Expected Background	0.71 ± 0.66	0.78 ± 0.36	0.48 ± 0.17	1.97 ± 0.77
Data	0	0	1	1

- Very few MC background events pass selection, large stat uncertainties
- Category III prediction taken from number of MC events with 2 real leptons and 2 real bs: 0.99±0.69
- Summary of background predictions (highlighted predictions are used for total):

Category	Data-driven pred	MC yield
I	0.74±0.27±0.74	0.98±0.34
II	$0_{-0}^{+0.4}$	0
III	N/A	0.99±0.69
IV	covered by I and II	0
Total prediction	1.73±1.12	

Systematics

- Uncertainty on Signal Acceptance and Efficiency:

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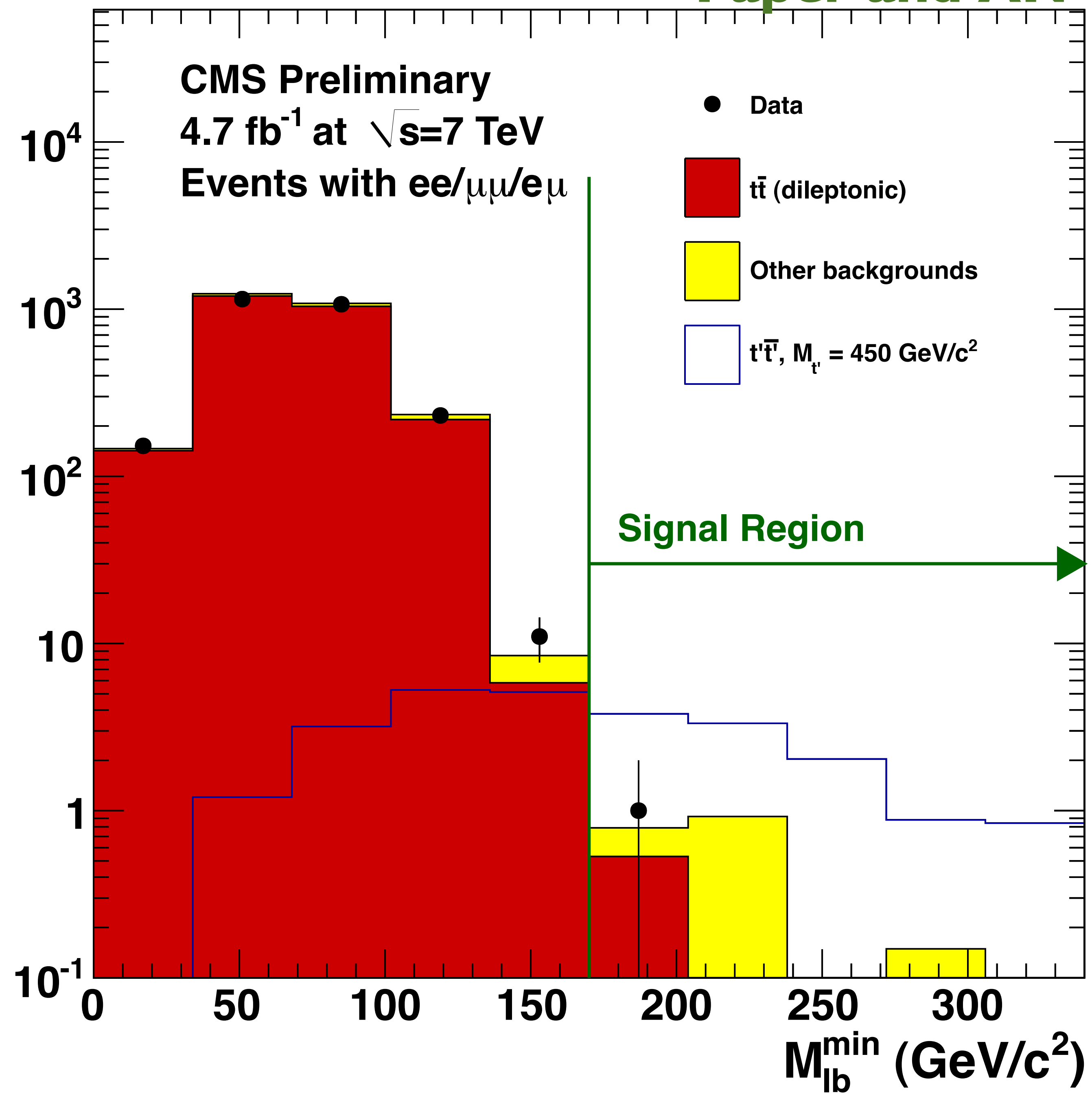
Source	Relative systematic uncertainty
b tagging efficiency	4% (15% for $p_T > 240$ GeV/c) per b jet
Trigger efficiency	2%
Lepton ID and iso	2% per lepton
Jet and E_T^{miss} energy scale	8%
Total	19%

- Luminosity uncertainty: 4.5%
- Uncertainties on data-driven background estimates dominated by 100% systematic on mistag estimate

Results

- 1 event observed (eμ channel)
- Prediction and observation consistent within the uncertainty
- No evidence of excess above SM
- Proceed to set 95% limits on t' pair production cross section

Paper and AN



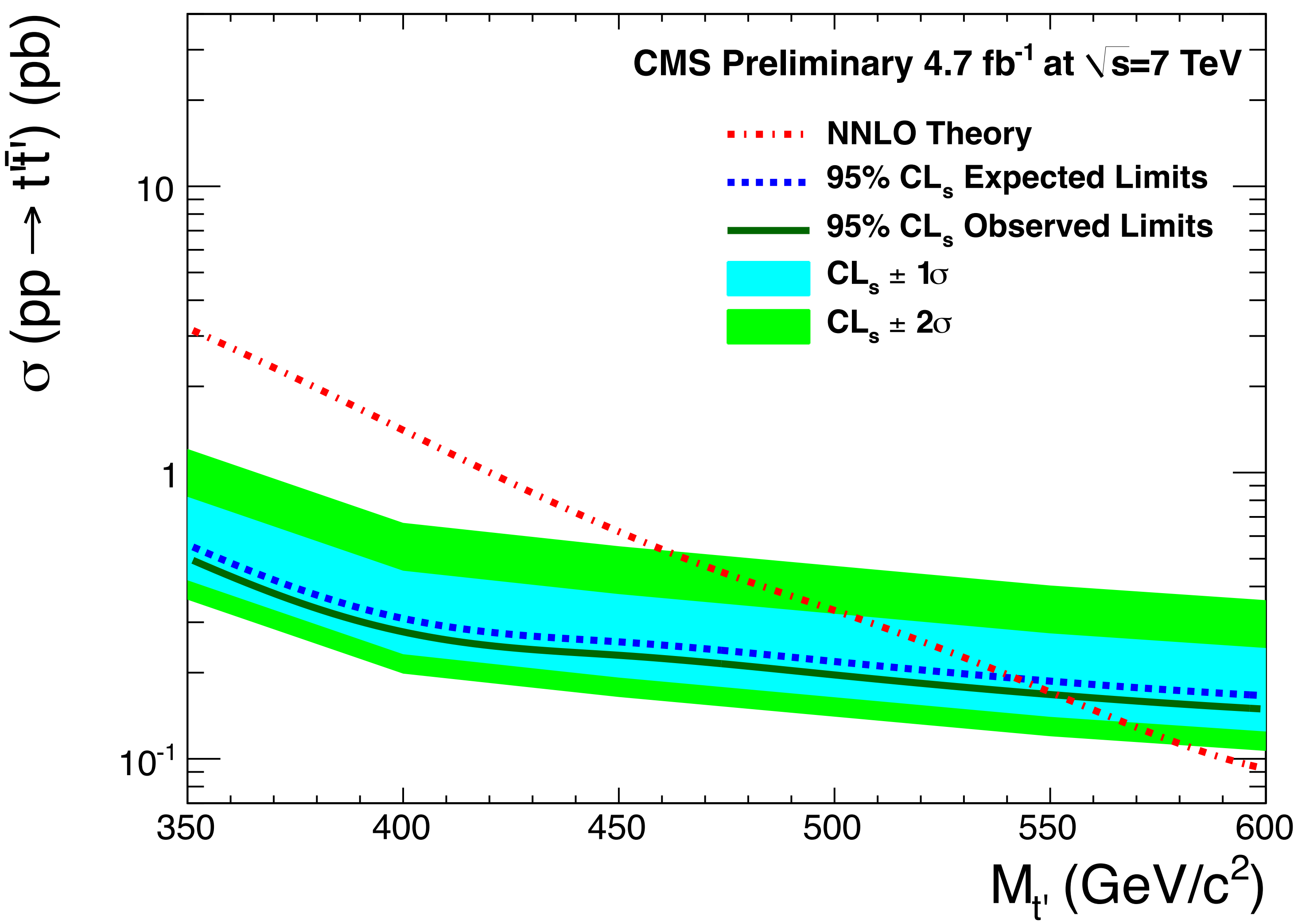
Paper and AN

Sample	Yield
Category I (data-driven)	0.74 ± 0.79
Category II (data-driven)	$0^{+0.4}_{-0.0}$
Category III (simulated)	0.99 ± 0.69
Total prediction	1.73 ± 1.12
Data	1

95% C.L. Limits

- Limits evaluated using LandS, taking into account change of signal acceptance with $M_{t'}$

Paper and AN



Paper and AN

Sample	Eff×Acc×BR
$t'\bar{t}'$, $M_{t'}$ = 350 GeV/c^2	0.16%
$t'\bar{t}'$, $M_{t'}$ = 400 GeV/c^2	0.29%
$t'\bar{t}'$, $M_{t'}$ = 450 GeV/c^2	0.35%
$t'\bar{t}'$, $M_{t'}$ = 500 GeV/c^2	0.41%
$t'\bar{t}'$, $M_{t'}$ = 550 GeV/c^2	0.48%
$t'\bar{t}'$, $M_{t'}$ = 600 GeV/c^2	0.54%

- Mass limits based on theoretical t't'bar cross sections (HATHOR)
- 552 GeV observed limit
- 542 GeV expected limit

Paper and AN

$M_{t'}$	350 GeV/c^2	400 GeV/c^2	450 GeV/c^2	500 GeV/c^2	550 GeV/c^2	600 GeV/c^2
Theory (pb)	3.200	1.406	0.622	0.330	0.171	0.092
Expected (pb)	0.560	0.309	0.256	0.219	0.187	0.166
Observed (pb)	0.503	0.278	0.230	0.196	0.168	0.149

Summary

- A search for a heavy top-like quark in the dilepton channel is performed with 4.7 fb^{-1} of 2011 data.
- Data driven estimates are made for mistag and fake backgrounds
- A MC estimate is used for backgrounds with real bs and leptons
- We calculate 95% C.L. upper limits on pp->t'tbar' production cross sections as a function of t' mass.
- Observed lower limit on the t' mass is 552 GeV

Backup

Lepton selections

Electron selection

- p_T > 20 GeV; |eta| < 2.5
- VBTF90 (cuts tightened to match CaloId+TrkIdVL HLT requirements)
- d0 (PV) < 0.04 cm, dz (PV) < 1 cm --calculated w.r.t. 1st good DA PV
- no muon $\Delta R < 0.1$
- <=1 miss hits, |dist| < 0.02 cm and < 0.02, CMS AN-2009-159
- Veto electrons with a supercluster in the transition region (1.44 <|eta| < 1.56)
- iso/p_T < 0.15 (EB pedestal subtraction 1 GeV, no fastjet correction)
- ecaliso/p_T < 0.2

Muon selection

- p_T > 20 GeV; |eta| < 2.4
- global and tracker muon
- chi^2/ndf < 10
- nValidHits > 10 -- to be updated to frac of validHits
- valid StandAloneHits > 0
- d0 (PV) < 0.02 cm, dz (PV) < 1 cm --calculated w.r.t. 1st good DA PV
- (p_T)/p_T < 0.1
- iso/p_T < 0.15 (no fastjet correction)

Triggers

- Double Electron
  - HLT_Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL
  - HLT_Ele17_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_Ele8_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL
  - HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL
- Double Muon
  - HLT_DoubleMu7
  - HLT_Mu13_Mu7
  - HLT_Mu13_Mu8
  - HLT_Mu17_Mu8
- Electron Muon
  - HLT_Mu17_Ele8_CaloIdL
  - HLT_Mu8_Ele17_CaloIdL
  - HLT_Mu17_Ele8_CaloIdT_CaloIsoVL
  - HLT_Mu8_Ele17_CaloIdT_CaloIsoVL

Trigger efficiencies

For the high p_T dilepton triggers, the efficiencies listed in Table 1, Table 2, Table 3 and Table 4 are applied to ee, $\mu\mu$ and $e\mu$ Monte Carlo Events. Details of the measurement of the trigger efficiencies are described in [12].

Table 1: The efficiency of the leading leg requirement for the double electron trigger, averaged over the full 2011 data.

Measurement	$0.0 \leq \|\eta\| < 1.5$	$1.5 \leq \|\eta\| < 2.5$
$20 \leq p_T \leq 30$	0.9849 ± 0.0003	0.9774 ± 0.0007
$p_T > 30$	0.9928 ± 0.0001	0.9938 ± 0.0001

Table 2: The efficiency of the trailing leg requirement for the double electron trigger, averaged over the full 2011 data.

Measurement	$0.0 \leq \|\eta\| < 1.5$	$1.5 \leq \|\eta\| < 2.5$
$20 \leq p_T \leq 30$	0.9923 ± 0.0002	0.9953 ± 0.0003
$p_T > 30$	0.9948 ± 0.0001	0.9956 ± 0.0001

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Table 3: The efficiency of the leading leg requirement for the double muon trigger, averaged over the full 2011 data.

Measurement	$0.0 \leq \|\eta\| < 0.8$	$0.8 \leq \|\eta\| < 1.2$	$1.2 \leq \|\eta\| < 2.1$	$2.1 \leq \|\eta\| < 2.4$
$20 \leq p_T \leq 30$	0.9648 ± 0.0007	0.9516 ± 0.0013	0.9480 ± 0.0009	0.8757 ± 0.0026
$p_T > 30$	0.9666 ± 0.0003	0.9521 ± 0.0005	0.9485 ± 0.0004	0.8772 ± 0.0012

Table 4: The efficiency of the trailing leg requirement for the double muon trigger, averaged over the full 2011 data.

Measurement	$0.0 \leq \|\eta\| < 0.8$	$0.8 \leq \|\eta\| < 1.2$	$1.2 \leq \|\eta\| < 2.1$	$2.1 \leq \|\eta\| < 2.4$
$20 \leq p_T \leq 30$	0.9655 ± 0.0007	0.9535 ± 0.0013	0.9558 ± 0.0009	0.9031 ± 0.0023
$p_T > 30$	0.9670 ± 0.0003	0.9537 ± 0.0005	0.9530 ± 0.0004	0.8992 ± 0.0011

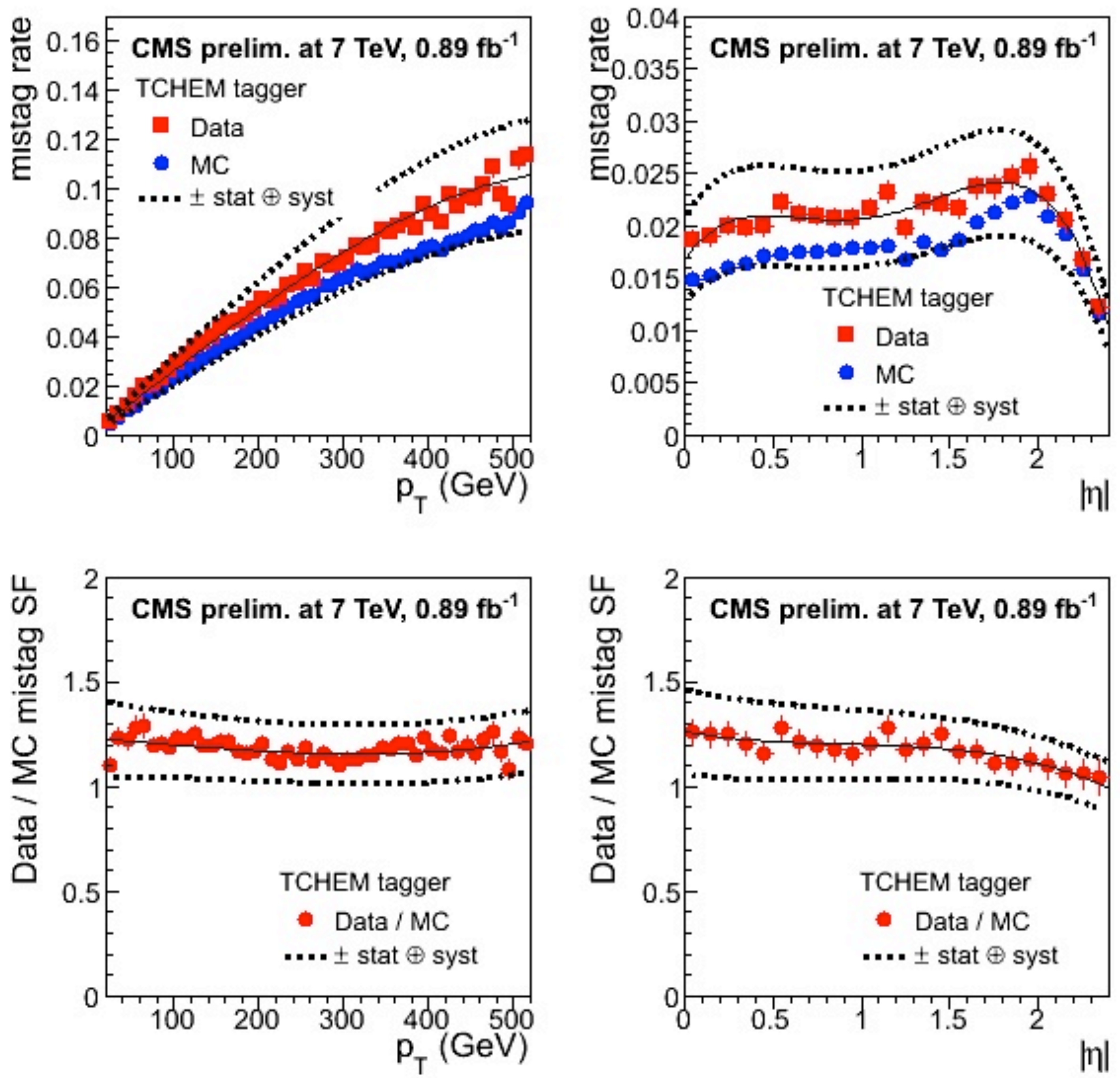
MC Samples

- TTJets_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1 , 165.8 pb
- TTJets_TuneZ2_7TeV-madgraph-tauola_Fall11-PU_S6_START42_V14B-v2 , 165.8 pb
- T_TuneZ2_tW-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 7.87 pb
- T_TuneZ2_t-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 41.92 pb
- T_TuneZ2_s-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 3.19 pb
- Tbar_TuneZ2_tW-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 7.87 pb
- Tbar_TuneZ2_t-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 22.65 pb
- Tbar_TuneZ2_s-channel_7TeV-madgraph_Summer11-PU_S4_START42_V11-v1 , 1.44 pb
- WJetsToLNu_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1 , 31314 pb
- DYJetsToLL_TuneD6T_M-50_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1 , 3048 pb
- DYToEE_M-20_CT10_TuneZ2_7TeV-powheg-pythia_Summer11-PU_S4_START42_V11-v1 , 1666 pb
- DYToMuMu_M-20_CT10_TuneZ2_7TeV-powheg-pythia_Summer11-PU_S4_START42_V11-v1 , 1666 pb
- DYToTauTau_M-20_CT10_TuneZ2_7TeV-powheg-pythia-tauola_Summer11-PU_S4_START42_V11-v1 , 1666 pb
- DYToEE_M-10To20_TuneZ2_7TeV-pythia6_Summer11-PU_S4_START42_V11-v1 , 3319.61 pb
- DYToMuMu_M-10To20_TuneZ2_7TeV-pythia6_Summer11-PU_S4_START42_V11-v1 , 3319.61 pb
- DYToTauTau_M-10To20_CT10_TuneZ2_7TeV-powheg-pythia-tauola_Summer11-PU_S4_START42_V11-v2 , 3319.61 pb
- WWJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola_ummer11-PU_S4_START42_V11-v1, 4.783 pb
- WZJetsTo2L2Q_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1, 1.786 pb
- WZJetsTo3LNu_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1, 0.856 pb
- ZZJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1, 0.30 pb
- ZZJetsTo2L2Q_TuneZ2_7TeV-madgraph-tauola_Summer11-PU_S4_START42_V11-v1, 1.0 pb
- ZZJetsTo4L_TuneZ2_7TeV-madgraph-tauola/_ummer11-PU_S4_START42_V11-v1, 0.076 pb
- TprimeTprimeToBWBWinc_M-350_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 3.200 pb
- TprimeTprimeToBWBWinc_M-400_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 1.406 pb
- TprimeTprimeToBWBWinc_M-450_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 0.622 pb
- TprimeTprimeToBWBWinc_M-500_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 0.330 pb
- TprimeTprimeToBWBWinc_M-550_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 0.171 pb
- TprimeTprimeToBWBWinc_M-600_7TeV-madgraph_Summer11-PU_S4_START42_V11-v2, 0.0923 pb

Mistag method: mistag rate

- Mistag rate is taken from CMS PAS BTV-11-001

http://cms-physics.web.cern.ch/cms-physics/public/BTV-11-001-pas.pdf



Mistag method closure test

- Prediction of the method compared to true count of events with mistags in MC
  - Total mistags predicted: 1.30±0.24 (uncertainties stat only)
  - Total mistags actual: 0.98±0.34

  - Repeat using Fall11 ttbar sample (20 times larger)
    - predicted (ttbar only): 0.27 ± 0.02
    - observed (ttbar only): 0.45 ± 0.09

  - Repeat for preselection region
    - predicted: 155.2 ± 1.6
    - observed: 288.3 ± 9.2